

Compressible-Fluid Dynamics *by* Philip A. Thompson

The Author

Philip Thompson taught at Rensselaer Polytechnic Institute (RPI) from the 1960s to the early 1990s when he retired. Philip had a special interest in thermodynamics and compressible flow which he explored with his students and collaborators in research at RPI and the Max-Planck-Institut für Strömungsforschung at Göttingen in the 1970s and 1980s. The emphasis in these studies was the importance of thermodynamic state and real fluid properties on compressible flow phenomena such as nozzle flows, shock and expansion waves. He was among the first to realize the significance of the *fundamental gasdynamic derivative* (see p. 252) to the existence of expansion shocks in real fluids and also the importance of *retrograde* behavior in fluids with large specific heats. Philip's major scientific achievement is arguably the demonstration of the richness of compressible flow with phase changes, exemplified by his discovery of partial and complete¹ liquifaction shocks. Philip's approach to compressible flow has promoted a new generation of compressible fluid studies in which realistic thermodynamic properties and phase change are emphasized.

The Text

Philip wrote *Compressible-Fluid Dynamics* when he was just beginning his study of real fluid effects and only a hint of his later research interests emerge in this text. The text is characterized by careful exposition, generality in the treatment of thermodynamics, copious illustrations, photographs and examples. The prose is fluid and I consider the presentation to be an exemplar of pedagogy. Originally published by McGraw-Hill in 1972, this text has served several generations of physicists and engineers as an introduction to the compressible flow of real fluids. Although dropped by McGraw-Hill after the first printing, interest in the book has remained high. Philip has reprinted the book several times. After a lapse of some years, Philip and Nancy have arranged to have the text reprinted, with corrections, by Hamilton Press. The result is a handsome bound volume with crisp reproduction rivaling the original production.

Obtaining Copies

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Corrections

The current set of corrections was generated by Joe Shepherd from notes by PAT and suggestions from colleagues. For the convenience of owners of the original edition and previous reprintings, these corrections are attached. Additional corrections and comments should be directed to:

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Joe Shepherd, Caltech, June 28, 1997 - revised August 27, 2003

¹Detleff, G., Thompson, P. A., Meier, G. E. A., and Speckmann, H.-D., 1979 An Experimental Study of Liquifaction Shock Waves, *Journal of Fluid Mechanics* 95 (2), 279-304.

p. 40 change symbol for dissipation in Table 1.2

Fluid Property	Inflow	Production
Mass	Convection	
Momentum	Convection	Applied force
Energy	Convection, heat, work	
Entropy	Convection, heat $\nabla \cdot$ absolute temp.	Dissipation Υ , temperature gradient (sum positive)

p. 58 change equation number

which connects the entropy to the other properties. Then (2.13) can be written

p. 80 change *increasing* to *decreasing*

This gives a ratio of specific heats $\gamma = 9/7$. Experimentally most diatomic gases, nitrogen and oxygen in particular, have $\gamma = 7/5$ at room temperature, gradually decreasing to $\gamma = 9/7$ at a few thousand degrees Kelvin (see Fig. 2.9). Equipartition thus gives an incorrect result, except at quite high temperatures. The reason is that classical statistical mechanics does not properly account for the quantization of molecular vibration (neither does

p. 94 remove 2 from inside surd

The definite integrals have the respective values $\sqrt{\pi}$ and $\sqrt{\pi}/2$, giving

p. 100 Table 2.5, molar mass of H₂ incorrect (should be 2.014)

Substance		\tilde{M}	P_c , atm	ρ_c , kg/m ³	T_c , K	$\frac{P_c v_c}{RT_c}$
He	Helium	4.003	2.26	69.3	5.19	0.308
Ar	Argon	39.948	47.99	531.	150.72	0.291
Xe	Xenon	131.30	58.	1105.	289.75	0.290
H ₂	Hydrogen	2.014	12.797	31.0	33.24	0.304
N ₂	Nitrogen	28.013	33.54	311.0	126.2	0.291
O ₂	Oxygen	31.999	50.14	430.	154.78	0.292
	Air	28.966	37.25	313.7	132.41	
H ₂ O	Water	18.015	218.17	317.0	647.29	0.230
CO ₂	Carbon dioxide	44.010	72.90	460.	304.20	0.275
CH ₄	Methane	16.043	45.8	162.	190.7	0.290
C ₃ H ₈	Propane	44.097	42.1	226.0	370.01	0.277
C ₄ H ₁₀	<i>n</i> -Butane	58.124	37.47	225.4	425.17	0.274

p. 105 add phrase to caption of Fig. 2.22

Figure 2.22: Compressible-fluid behavior of a metal. Penetration of an aluminum jet (e.g., an aluminum rod) at 15 km/s into an aluminum target. The flow is two-dimensional, with jet thickness 1 mm. Successive frames are at 0.10, 0.20, 0.30, 0.45 μ s. (*Courtesy of F. H. Harlow.*)

p. 123 Table 3.2, add femto definition

Exponential	Prefix	Abbreviation
10 ¹²	tera	T
10 ⁹	giga	G
10 ⁶	mega	M
10 ³	kilo	k
10 ⁻³	milli	m
10 ⁻⁶	micro	μ
10 ⁻⁹	nano	n
10 ⁻¹²	pico	p
10 ⁻¹⁵	femto	f

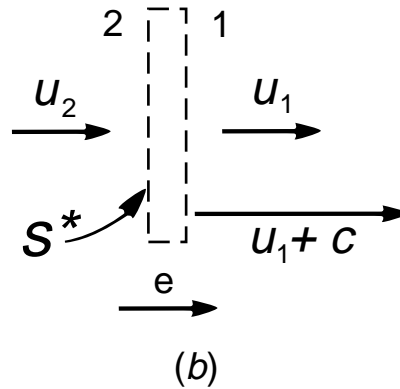
p. 138 correct Eq. 3.42

$$c^2 \equiv \left(\frac{\partial P}{\partial \rho} \right)_s \tag{3.42}$$

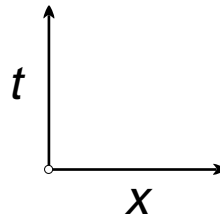
p. 139 correct Eq. 3.44

$$\begin{aligned} \nabla \cdot \mathbf{u} = & \frac{1}{2c^2} \mathbf{u} \cdot \nabla \mathbf{u}^2 - \frac{\mathbf{u} \cdot \mathbf{G}}{c^2} + \frac{1}{c^2} \left[\frac{1}{2} \frac{\partial u^2}{\partial t} - \frac{1}{\rho} \frac{\partial P}{\partial t} \right] \\ & - \frac{\mu}{\rho c^2} \left[\mathbf{u} \cdot \nabla^2 \mathbf{u} + \left(\frac{\mu_v}{\mu} + \frac{1}{3} \right) \mathbf{u} \cdot \nabla (\nabla \cdot \mathbf{u}) \right] \\ & + \frac{1}{c_p} \left(\frac{\partial v}{\partial T} \right)_p [\Gamma + \kappa \nabla^2 T] \end{aligned} \tag{3.44}$$

p. 185 swap state symbols 1 and 2 in Fig. 4.8 (b)



p. 191 add $x-t$ axes to Fig. 4.13 (b) and (c)



p. 281 change exponent in Eq. 6.9

$$\frac{A}{A_*} = \frac{1}{M} \left(\frac{2}{\gamma + 1} + \frac{\gamma - 1}{\gamma + 1} M^2 \right)^{(\gamma+1)/(2(\gamma-1))} \tag{6.9}$$

p. 338 The statement at the bottom of the page: “It appears that $P < \rho c^2$ for all known fluids” is a conclusion that is restricted to substances at normal temperatures and pressures. Under high pressures, such as created by high explosive loading, P can easily exceed ρc^2 by one to two orders-of-magnitude. I did not include this correction in the 1997 reprinting since it would require substantial exposition and it does not change the conclusions of this section.

p. 366 add the symbol Δ

as shown in Fig. 7.41.

The shock thickness Δ is somewhat arbitrary. If the edges of the shock are reckoned to be at $(u - u_2)/(u_1 - u_2) = 1 - \epsilon$ and $(u - u_2)/(u_1 - u_2) = \epsilon$, then (7.106) gives

p. 368 omission in Eqn. 7.111

$$\frac{\gamma + 1}{2} \frac{c_1}{\delta} \frac{|[w]|}{c_1} x = \ln \frac{\frac{\rho}{\rho_1} - 1}{1 - \frac{\rho}{\rho_1} \frac{\rho_1}{\rho_2}} \quad (7.111)$$

p. 373 Change to equation given in Problem 7.26

$$-\frac{[w^2]}{2c_1^2} = \Pi - \frac{1}{2}\Pi^2 + \frac{1}{2}\Gamma_1\Pi^3 \dots$$

p. 421 Change Case c

Case a: $M_{1n} = 1.25$

Case b: $M_{1n} = 1.50$

Case c: $M_{1n} = 2.50$

p. 446 Extend surd in first arctan argument of Eq. 9.6. Note, signs were switched in argument in earlier version of this correction. Fixed on July 17, 2003. (Thanks, Riccardo!)

$$\omega(M) = \sqrt{\frac{\gamma + 1}{\gamma - 1}} \tan^{-1} \sqrt{\frac{\gamma - 1}{\gamma + 1}} (M^2 - 1) - \tan^{-1} \sqrt{M^2 - 1} \quad (9.6)$$

p. 500 change value of last line in Eq. 10.40

$$\begin{aligned}
 k_1 &\equiv \frac{13\gamma^2 - 7\gamma + 12}{(3\gamma - 1)(2\gamma + 1)} \\
 k_2 &\equiv \frac{-5(\gamma - 1)}{2\gamma + 1} \\
 k_3 &\equiv \frac{3}{2\gamma + 1} \\
 k_4 &\equiv \frac{13\gamma^2 - 7\gamma + 12}{(2 - \gamma)(3\gamma - 1)(2\gamma + 1)} \\
 k_5 &\equiv \frac{2}{\gamma - 2}
 \end{aligned} \tag{10.40}$$

p. 577 add additional thermodynamic identities to B.9 and B.14

$$\left(\frac{\partial c_p}{\partial P}\right)_T = -T \left(\frac{\partial^2 v}{\partial T^2}\right)_p \quad \text{and} \quad \left(\frac{\partial c_v}{\partial v}\right)_T = T \left(\frac{\partial^2 P}{\partial T^2}\right)_v \tag{B.9}$$

$$\left(\frac{\partial T}{\partial P}\right)_s = \frac{T}{c_p} \left(\frac{\partial v}{\partial T}\right)_p \quad \text{or} \quad \left(\frac{\partial T}{\partial P}\right)_s = \frac{(\gamma - 1)v^2}{c^2} \left(\frac{\partial T}{\partial v}\right)_p \tag{B.14}$$

p. 583 change to bar as pressure unit

$$1 \text{ atm} = 760 \text{ mm Hg} = 1.01325 \times 10^5 \text{ N/m}^2 = 14.696 \text{ lb}_f/\text{in}^2$$

$$1 \text{ bar} = 10^5 \text{ N/m}^2 = 0.98692 \text{ atm}$$

$$1 \text{ torr} = 1 \text{ mm Hg}$$

$$1 \text{ kg}_f/\text{cm}^2 = 0.98066 \text{ bar} = 0.96784 \text{ atm}$$

p. 584 add gallon conversion factor

$$1 \text{ liter} = 0.035315 \text{ ft}^3$$

$$1 \text{ km} = 0.62137 \text{ miles}$$

$$1 \text{ mile} = 1.6093 \text{ Km}$$

$$1 \text{ gallon (US)} = 231 \text{ in}^3$$

p. 640 change entries in Table F.2 for hydrogen (H_2)

Gas	Molecular Weight \bar{M}	Gas Constant $R, m^2/(s^2)(K)$	Specific-heat Ratio γ	Density $\rho, kg/m^3$	Sound Speed $c, m/s$
He	4.0026	2,077.2	1.667	0.1664 [†]	1,007.4 [†]
Ar	39.948	208.13	1.670	1.662	319.0
Xe	131.30	63.32	1.667	5.459 [†]	175.9 [†]
H_2	2.014	4,128.1	1.406	0.0837	1,304.4
N_2	28.0134	296.80	1.401	1.165	349.1
O_2	31.9988	259.83	1.397	1.332	320.5
Air	28.966	287.03	1.402	1.205	343.3
CO	28.0106	296.83	1.402	1.165	349.1
CO_2	44.0100	188.92	1.297	1.839	266.2
CH_4	16.0431	518.25	1.31	0.594	446.1 [†]
CF_4	92.0367	90.34	1.16	3.673	173.3 [†]